REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)* See Attached List
4. TITLE AND SUBTITLE See Attached List		**5a. CONTRACT NUMBER** N/A
		5b. GRANT NUMBER N/A
		5c. PROGRAM ELEMENT NUMBER N/A
6. AUTHOR(S) See Attached List		**5d. PROJECT NUMBER** N/A
		5e. TASK NUMBER N/A
		5f. WORK UNIT NUMBER N/A
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) See Attached List		**8. PERFORMING ORGANIZATION REPORT NUMBER** N/A
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Kristi Laug AFRL/PROP 1950 Fifth Street Wright-Patterson AFB OH 45433 937-255-3362		**10. SPONSOR/MONITOR'S ACRONYM(S)** N/A
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) N/A

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution Statement A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

N/A

14. ABSTRACT

20030113 075

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: UNCLASSIFIED			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Kristi Laug
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	Unlimited Distribution	See Attached List	**19b. TELEPHONE NUMBER** *(include area code)* 937-255-3362

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

TITLE	AUTHORS	DATES	PAGES
The Place of Solar Thermal Rockets in space	C. C. Selph	May 81	24
Solar Thermal Propulsion from Concept to Reality	Karl J. Iliev	Aug 1996	11
Solar BI-Modal System Concept: Mission Applications, A Preliminary Assessment	Kristi K. Laug, Michael R. Holmes Kurt O. Westerman		5
Dual-Propulsion Technology Reusable Orbit Transfer Vehicle Study	Travis Elkins, Terence Galati		7
Studies of Hafnium-Carbide Wafers using a Thermogravimetric	Domingo G. Castillo, Paul F. Jones		11
One Dimensional Model of a Solar-Thermal Thruster Using a Porous Absorber/Heat Exchanger	Michael R. Holmes	October 15, 1993	29
Evaluation of Hafnium-Carbide Wafers for use in a Solar Calorimeter	Kristi K. Laug, Alan J. Baxter		7
Solar Thermal Propulsion Experiments Design	Kristi K. Laug	1996	11
Porous Disk Test Bed Report of Results	Richard Hurtz	Aug 10, 1990	24
The Solar Propulsion Concept is Alive and Well at the Astronautics Laboratory	Kristi K. Laug	Nov 26, 1993	70
Foam Inflated Rigidized Truss Structure Developed for an SRS Technologies Solar Concentrator	Dean M. Lester, David M. Cannon	1996	8
Fabrication of Thin Film Concentrators for Solar Thermal Propulsion Applications	Paul A. Cierow	1991	7
Scaling Characteristics of Inflatable Paraboloid Concentrators	Mitchell Thomas, Gordon Veal	1991	6
AFRPL Solar-Thermal Rocket Activities	C.C. Selph, G.J. Naujokas	March 1984	9
Dependence of Solar-Thermal Rocket Performance on Çoncentrator Performance	Michael R. Holmes, Kristi K. Laug	1995	12
A Comparison of the Performance of Seamed and unseamed Inflatable Concentrators	Arthur Palisoc, Mitchell Thomas	1995	10
Society for the Advancement of Material and Process Engineering	Thomas C. Walton, James V. Crivello		10
Ideal Performance of Off-Axis Paraboloid Concentrators for Solar Thermal Propulsion	Michael R. Holmes		7
A Performance Evaluation of an Inflatable Concentrator for Solar Thermal Propulsion	J.P. Paxton, M. R. Holmes		10
Prediction of the Response of a Polyimide Concentrator for Solar Thermal Propulsion	Paul A. Gierow, William R. Clayton, James D. Moore		8
Inflatable Concentrators for Solar Themal Proulsion	William R. Clayton, Paul A. Gierow	1992	6
The Long Term Storability and Expulsion ofRocket Propellants and Oxidizers	Gordon David Elder	Aug 13, 1987	5
Prediction of the Response of a PolyimideConcentrator forSolar Thermal Propulsion	Paul A. Gierow, James D. Moore		11
Conceptual Design Study of a Solar Concentrator	R. Prasinghe, Kristi K. Laug		13
PL (OLAC)/RKAS Concentrator Information	Michael R. Holmes	Feb 11, 1993	29
Dependence of Solar-Thermal Rocket Performance on Concentrator Performance	Michael R. Holmes, Kristi K. Laug	1995	12
Thruster Interface	Michael R. Holmes	May 4, 1994	23
Cumulative Power Plots	Kristi K. Laug		87

5

Selph, C.C. and Naujokas, G.J.

AFRPL SOLAR-THERMAL ROCKET ACTIVITIES

MAR 1984

C. C. Selph
G. J. Naujokas
AF Rocket Propulsion Laboratory
Edwards AFB CA 93523

ABSTRACT

Earth orbital maneuvers, particularly orbit raising, provide the most important and extensive propulsion tasks in space and are not ideally served by either chemical rockets with their comparatively low Isp or electric rockets with their low thrust. For several years the Air Force Rocket Propulsion Laboratory (AFRPL) has investigated solar thermal propulsion as a potential way of filling this gap in propulsion capability. The concept makes use of concentrated sunlight to heat hydrogen to temperatures approaching 5000 Deg R for expansion through a converging-diverging nozzle. The payload advantages which accrue from the high Isp (over 800 seconds) in various mission scenarios were determined analytically and a combined in-house and contractual investigation was launched to provide a demonstration and evaluation of the concept within the limits of a ground test facility. The design and fabrication of a nominal one pound thrust solar rocket was contracted out, and an in-house project was initiated to design and build a facility for testing the solar engine. In addition the analysis of alternative thruster concepts has been accomplished.

INTRODUCTION

We last reported our efforts on solar-thermal rockets in New Orleans two and a half years ago (1). As befits an initial report, that presentation had strong historical and analytical overtones, and it ended with an outline of our plans for what has become the past two years. The present report will cover the actual course of events over this period, and then bravely attempt a forecast of the next cycle. In brief we have been designing and building, and to some extent redesigning and rebuilding. No hot firings have been accomplished, but most of the facility has been completed. The thruster itself is also nearly ready for delivery to us.

To recap, the solar-thermal rocket uses highly concentrated sunlight to heat a working fluid for expansion through a more or less conventional converging-diverging nozzle. Typically the propellant is hydrogen, although ammonia might be used where long term storage is more important than ultimate Isp. No oxidizer is needed, so molecular weight is low, and Isp values of 870 seconds for H_2 and 500 seconds for ammonia are believed reasonable goals. More advanced thrusters might add two hundred seconds more. The most characteristic feature of the propulsion system is the pair of large, paraboloidal mirrors, which collect and concentrate the

sunlight several thousand fold into the absorber (Fig. 1). The collectors are 45 degrees off-axis parabolas, capable of tracking the sun by rotating around an axis perpendicular to the thrust axis, and also by rotating the vehicle around the thrust axis as necessary. They are envisioned as inflatable structures to save weight.

Solar thrusters offer a capability intermediate between chemical propulsion and electric propulsion, both in terms of thrust and specific impulse. Typical thrusts may be in the tens of pounds, leading to manuever times of about a month in orbit raising from low earth to geosynchronous altitudes; and payload capability may be up to 40% greater than cryogenic, high performance chemical stages.

Current AFRPL efforts are pointed towards ground demonstration of a small solar thruster. The thruster has been designed and is being built under contract by Rocketdyne, and is scheduled to be tested in a facility being developed in-house.

THE SOLAR THRUSTER

The specifications for the thruster were originally described in terms of the flux characteristics of a commercially available solar concentrator, planned for the tests. As worked out in the analytical phase, this yielded an expected thrust of about 0.8 pounds. An Isp goal of 800 seconds was identified.

The Rocketdyne effort included a concept development phase which analyzed five thruster types. These were a windowless heat exchanger, a windowed heat exchanger, a windowed rotating particle bed heat exchanger, and two varieties (also windowed) in which the light would be absorbed by particulate matter entrained in the flow. As a result of the analysis the windowless thruster was selected as being most practical; and it was judged capable of meeting the Isp goal even if some of the more complex designs were higher.

The ground test thruster design is shown in Figure 2. Perhaps the most noticeable feature is the large number of windows in this "windowless" design. These should be understood to be part of the facility rather than the thruster and more will be said about them later. The dividing line between the thruster and the facility is indeed subtle and changed in certain respects during the course of the contract as the complexities of integrating the two entities emerged. Aside from integration considerations the job became more difficult as analysis progressed and the hardships of providing adequate thermal control were fully revealed. The fabrication phase was impacted as more heat shields and more ceramic parts with difficult shapes were injected into the design. And finally we joined the ranks of a select few who know first hand what a commitment to rhenium parts can do to schedules and costs. The thruster is now scheduled to be delivered in March, a year and a half late.

Few shortcuts are possible in demonstrating a credible solar rocket. It gets hot--far beyond usual heat exchanger experience. Energy loss through re-radiation would be severe without controls; and the problem does not go away with increasing thrust as it does in conventional rockets. It would not be enough to just cool a marginally designed ground test unit with water and correct the test results. Demonstration of heat loss control is part of the job, co-equal with demonstrating Isp and lifetime. The thruster/absorber is nested inside a series of six concentric cylindrical radiation shields, two of tungsten (the innermost), and four of molybdenum. The space between the outer two molybdenum shields is filled by a cylinder of aluminum oxide for further heat loss control. This assembly sits in a windowed vacuum canister whose walls carry a regenerative flow of hydrogen propellant. With all these thermal control features, parts of the canister wall still reach 1000 degrees Fahrenheit according to analyses.

The solar absorption cavity at the center of these insulation structures is formed by winding five parallel rhenium tubes into a cylinder three inches in diameter and nine inches long. One end of the cylinder is open to admit sunlight and the other end is closed by winding inward in a hemispherical fashion until a closure plug of graphite is reached. The wound coils of the absorber slip inside a graphite sleeve which supports them against thermal sagging. All graphite parts are rhenium - coated to prevent carbon sublimation from contaminating the window. The heated hydrogen flowing in the five tubes is collected into a nozzled rhenium thrust chamber, provided with a pressure transducer line and a tungsten/tungsten-rhenium thermocouple. Thermocouples are also provided at fifteen locations along the wound coils. The thruster nozzle is contoured to an area ratio of 20, which is as high as can be profitably used due to boundary layer losses that affect such small thrusters. It is mainly the effects of the boundary layer that reduce the expected delivered Isp to 809 seconds from the 870 seconds expected from the 20 pound thrust rocket assumed in earlier mission studies.

THE TEST FACILITY

Overview. The finished facility will consist of a small, windowed altitude chamber containing the thruster and thrust stand, perched some twelve feet above the floor-level at the focal plane of a solar concentrator mirror. Both the test stand and concentrator are housed in a 70ft x 63ft metal shed with its northeast wall removed. The concentrator faces out the exposed direction to a sun tracking heliostat located beyond the shadow of the building. The lack of north-south orientation is perhaps unusual, and is an artifact of selecting an existing unused building. The handicap in terms of reduced sunlight is small and more than made up by the convenience of locating the heliostat in the wind shadow of the shed. Our prevailing winds are from the southwest and are regularly strong enough to be of concern from a vibration standpoint.

Altitude Chamber. The thruster nozzle exit pressure is estimated at 0.3 psia, and its environment is reduced to that pressure during firing by enclosing the thruster in an altitude chamber. The chamber is partly self-pumped by exhausting the thruster through a diffuser, and it is aided by a nitrogen ejector mounted coaxially with the diffuser. The thruster, including its vacuum canister, and the thrust stands are mounted in a horizontal configuration within the close confines of the 30 inch diameter chamber.

Thrust Stand. The weight of the thruster, canister and mountings is about 340 pounds. This mass plus the thrust plane is supported from below by the propellant feed line, and the coolant, vacuum and transducer lines. These lines form vertical support posts and are also the flexures for the thrust stand. Strain gage measurements of thrust accurate to 1% are provided for, and the calibration is performed remotely by a dead weight calibration system. The high temperature of the canister (up to 1000 F) makes it necessary to water cool the thrust plane and strain gage.

Windows. Much attention has been given to this facility item. A minimum of two windows are required: one to separate the altitude pressure from the ambient atmospheric pressure, and one to separate the altitude pressure from the much lower pressure (below 10^{-3}mm Hg) of the vacuum canister surrounding the absorber coils. The peak solar flux approaches 400 w/cm^2 for the window closest to the focal plane, which of course is also the window closest to the re-radiated flux from the absorber coils.

Quartz was selected as the window material due to its low absorption in the visible spectrum and the near ultraviolet and near infrared. Quartz does have absorptions in the 2.2 micrometer wavelength region, however, and a heavy absorption between 2.5 and 3.0 micrometers due to hydroxyl bands. There is sufficient radiative flux in these bands to cause severe window heating, given the poor ability of quartz to conduct heat away from hot spots. The initial approach of coating the windows with "heat mirrors" such as indium tin oxide to reflect away damaging wavelengths has been abandoned. Sufficient information about the absorption coefficient of all such coatings in the crossover region (from transparency to reflections) has been obtained to show that the approach is counterproductive. Instead an active cooling plan has been adopted. The inner window is paired with a second window; and the narrow space between them is filled with a flow of an inert perfluoroether from 3M Company, which has no absorption below seven micrometers.

Concentrator Mirror. Initially we planned to share a solar concentrator acquired commercially by another AFRPL project. However, this concentrator was found to perform well short of its advertised concentration ratio and was abandoned. Its only remaining influence is in the power and flux profile, which were transferred

from brochures into the Rocketdyne contract and imbedded in the thruster design before its problems were uncovered. These specifications were a 24.7kw net total power within a 6 cm diameter spot size and a peak flux density of 1110 watts/cm^2. These are tight, but attainable specifications; and, rather than delay the contract, it was decided to leave them intact. Any replacement concentrator would have to accept the burden of meeting them.

Many options were considered, but the solution arrived at was to build a concentrator in-house with contracted assistance from the Jet Propulsion Laboratory (JPL). JPL has, until recently been the Department of Energy's designated center for point focussing concentrator research, with engineering, design and fabrication responsibilities at their Pasadena and Foothill facilities and test operations at the Edwards Test Station (ETS) 20 miles from the AFRPL.

ETS had two identical eleven meter concentrators in operation known as Test Bed Concentrators One and Two (TBC-1 and TBC-2) which were each built by mounting some 260 rectangular mirror facets to a large radar dish. The technology for manufacturing successful facets had been perfected and proven over the past several years, which minimized our risk. A scaled down version of the TBC's was designed at AFRPL using a ray-tracing code to match the geometry of the concentrator to the requirements of the solar thruster and the profile of a surplus heliostat we had obtained from the Naval Weapon Center. In one respect the AFRPL concentrator is simpler than TBC, since the sun-tracking heliostat relieves it of the necessity to follow the sun. The design that emerged was an oval concentrator 20 feet high and 25 feet wide, with a focal length of about 14 feet. A petalline structure was designed rather than the grid-like layout of the TBC facets. But the identical glass-mirror to foam-glass backing technology was adopted for the facets.

In this approach mirrors made from thin, high transparency glass specially developed for solar purposes are forced into a gentle curvature (twice the desired focal length). This is accomplished by evenly pressing the mirror into the hemispherical contour of a pre-ground slab of foam-glass (a commercial insulating material) and bonding it there in a permanent condition of strain. The two inch thick facet is cut to shape, sealed against moisture, provided with mounting brackets, and painted. Its radius of curvature and RMS surface error is measured prior to acceptance. Facets of this general description have proved trouble free in service at JPL-ETS despite the daily and seasonal temperature extremes of a desert environment. None of the AFRPL facets has yet failed in storage during the several months since their manufacture, even though they are in a more strained condition due to the smaller radius of curvature of the AFRPL concentrator.

TEST PLAN

The test program will include relatively short duration tests, nominally a minute or so, to determine steady state performance data such as peak temperatures, specific impulse, and energy efficiency; and it will include longer duration tests to gain an understanding of the endurance of the thruster. An accumulated time at temperature of ten hours has been set as an initial goal; but it should be mentioned that the thruster selection criteria given to Rocketdyne required a theoretical capability of 1000 hours.

Actual performance will depend upon the atmospheric conditions at test time as well as the capabilities of our solar concentrator. Corrections for conditions will be applied using solar flux information obtained with a pyreheliometer. This correction is difficult since the optics of the pyreheliometer cannot mimic exactly those of the concentrator. It will thus be necessary to perform a preliminary set of calibrations using a water-cooled cavity calorimeter in place of the thruster.

RELATED ACTIVITIES

Rotating Bed Thruster Analysis. The windowless heat exchanger presently being examined is the most limited in terms of temperature and Isp of any of the concepts studied by Rocketdyne. All the alternatives we have examined require windows, whose problems we will soon sample, though in a facility context. Assuming that viable window strategies are found, one of the more attractive alternative thruster designs is the rotating bed heat exchanger. In this concept hydrogen propellant blows inward through a cylindrical packed bed of refractory material, such as tantalum carbide or hafnium carbide heated on its inner surface by concentrated sunlight. The bed is held against an outer porous cylinder by centrifugal force. The major advantage is the higher melting point of these bed materials, and the essential lack of mechanical demand upon them. The complications of rotating machinery are a disadvantage, or course, but presumably are solvable problems if the bed is successful in keeping heat loads away from the bearings and seals. Thus the primary question is the heat loss control offered by the bed.

This question is being addressed at a low level in an in-house effort. Only preliminary information is available as yet; but it indicates that the "dynamic insulation" provided by the inward blowing hydrogen is not so large a factor as had been hoped, due to the small flow rates and large areas to be cooled. These studies will continue.

Inflatable Mirrors. Crucially important to the long range feasibility of solar rockets is the ability to manufacture very large light-weight, storable, deployable concentrator mirrors. The best hope for this at present is the inflatable concentrator. Such structures have also been proposed as space deployable

microwave dishes. These combined interests were advertised through the Small Business Innovative Research Program, and resulted in two successful proposals. Both programs are concerned with fabrication techniques, particularly with respect to ways of reducing surface imperfections due to seaming. Film materials will also be studied, as will an electrostatic concept for figure control.

Plume-Concentrator Interactions. A subset of the concentrator problem is what happens to the concentrator in space when the thruster is firing and parts of the plume impinge on it. This was addressed briefly by Rockwell [2] in the context of contamination. A related problem is concentrator displacement, misalignment or distortion. Even though the plume pressures are small in the forward hemisphere, the areas affected are large, and the resisting masses, pressures and structural strengths are similarly small. The problem is scheduled to be studied in-house.

FUTURE PLANS

The testing of solar rockets under the current in-house project will continue through FY84 and into FY85, as will the related efforts on inflatable concentrators and analysis of the rotating bed heat exchanger. At the conclusion of this phase we expect to have identified any obvious "show stoppers"; and we will have a firmer basis for extrapolating the performance capabilities of solar thermal rockets. Furthermore we will be in a better position to judge the most deserving options for our limited budget. Attainment of the performance goals with the windowless heat exchanger will argue for continued exploration of that approach: more extensive testing to define thruster temperature and endurance limits, scale-up to higher thrusts, reducing component masses, re-configuring for side-entry of a pair of beams, and others. A significant shortfall would perhaps argue for emphasizing alternative concepts, such as the rotating bed heat exchanger, assuming that approach does not falter under analytical scrutiny also now underway.

CONCLUSION

Despite delays in both the thruster and the test facility, the solar rocket program is continuing. The activities are best described as research, in that many questions of a fundamental nature remain unanswered. These include achievable Isp, efficiency and thruster life. Successful demonstration of program goals will open the way for a propulsion concept that may be the best suited for the important task of orbit raising.

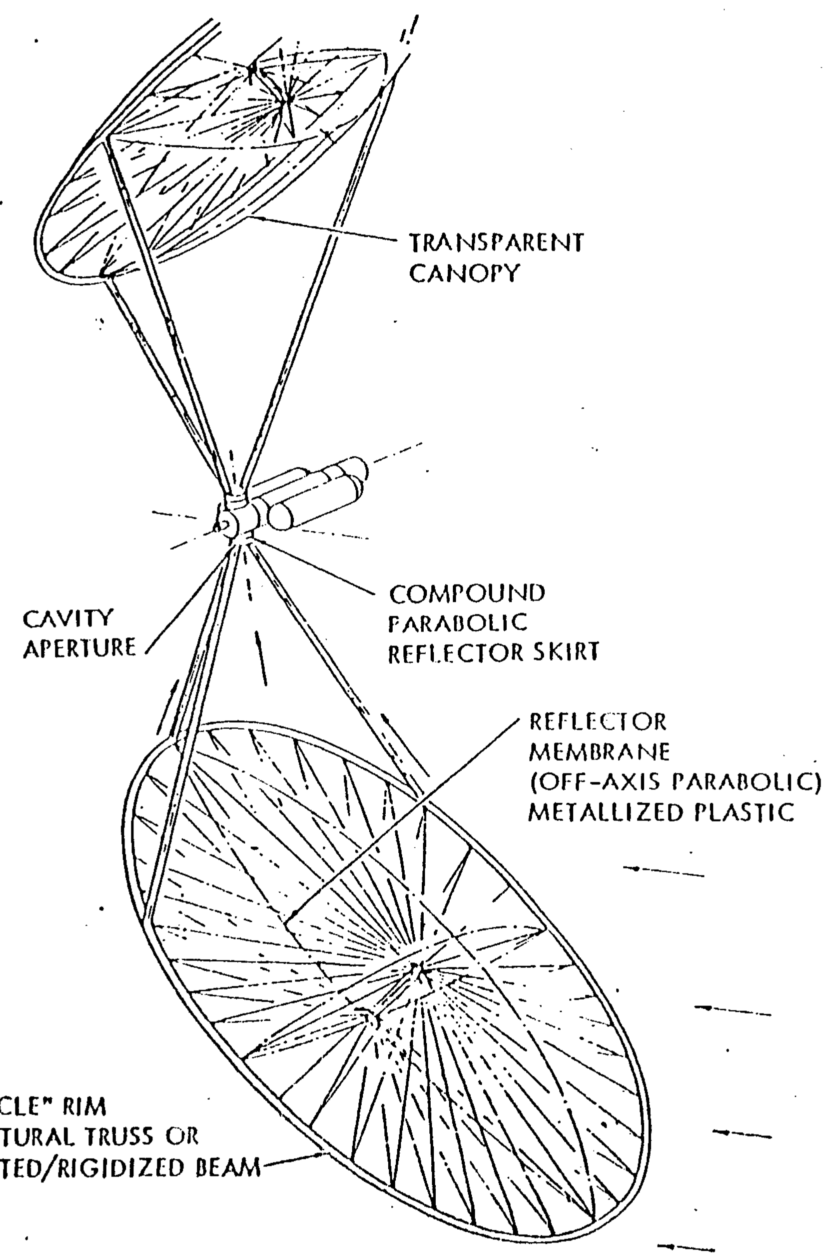
REFERENCES

1. C. C. Selph, "The Place of Solar Thermal Rockets in Space", 1981 JANNAF Propulsion Meeting, New Orleans LA, 26-28 May 1981

2. F. Etheridge, "Solar Rocket System Concept Analysis", Rockwell International Final Report,
Contract F04611-80-C-0007, AFRPL-TR-79-79, December 1979.

FIGURE 1

NON-RIGIDIZED INFLATABLE CONCENTRATOR ....



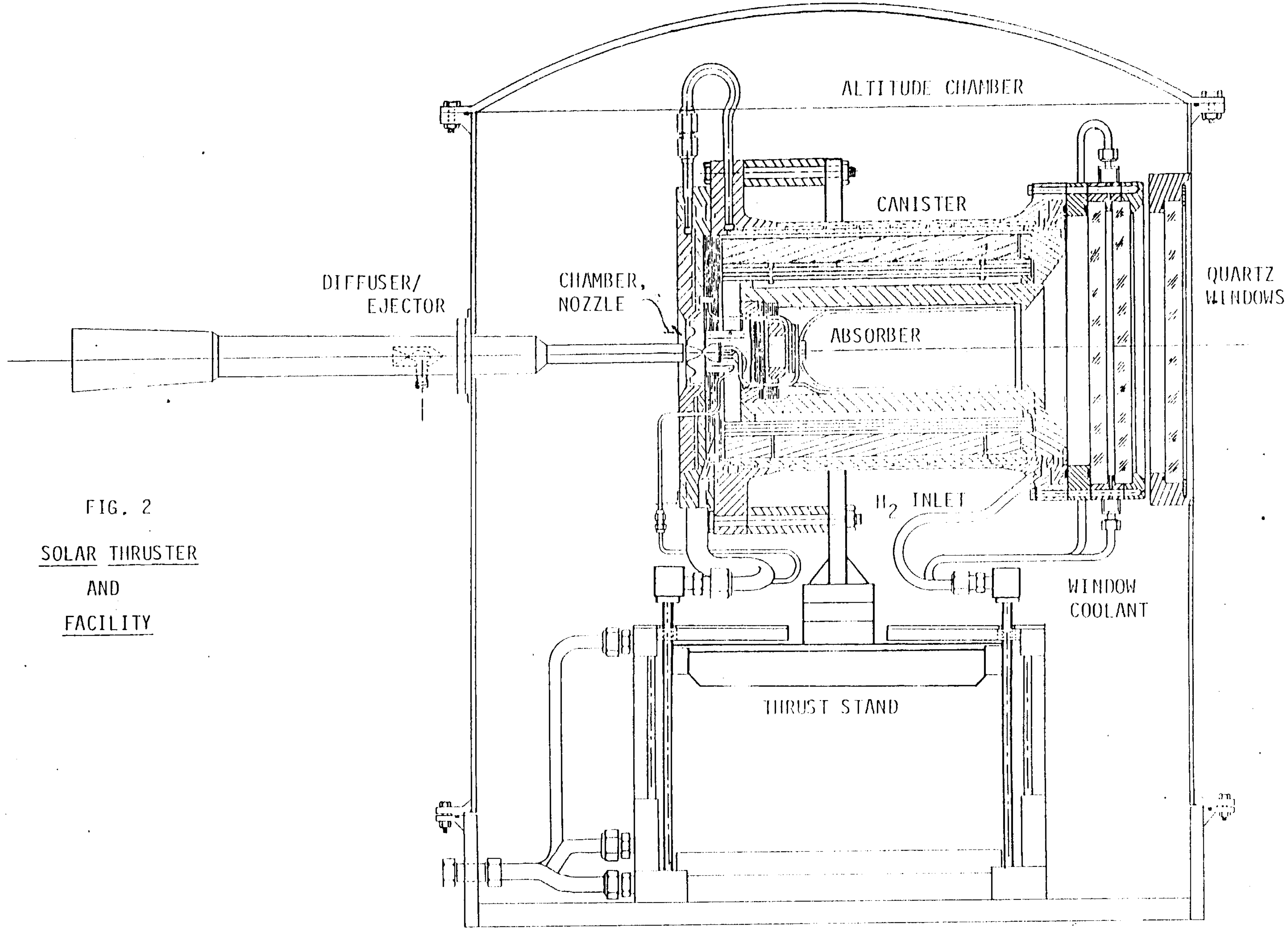


FIG. 2

SOLAR THRUSTER
AND
FACILITY